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Global monthly water stress: 2. Water demand and severity of water stress

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1. Introduction

[2] In this series of two papers [see also *van Beek et al.*, 2011], global water stress at a monthly time scale is assessed, in order to capture the seasonal phase shifts in peak water demand and water availability and to assess both frequency and persistence of water stress as captured by a dynamic water stress index (DWSI). In this study water demand concerns the net water demand (i.e., water withdrawal minus return flow) from surface fresh water (i.e., water in rivers, lakes and reservoirs) or blue water. Water stress is a measure of the amount of pressure put on blue water resources by their use [*Flörke and Alcamo*, 2004]: the higher the water stress, the more vulnerable the population in a region will be to water scarcity. In 1997, the United Nations estimated that approximately one third of the world's population currently lives in countries experiencing moderate to severe water stress [*World Meteorological Organization* (*WMO*), 1997]. Previous studies [e.g., *Arnell*, 1999, 2004; *Vörösmarty et al.*, 2000; *Oki et al.*, 2001; *Alcamo and Henrichs*, 2002; *Alcamo et al.*, 2003b; *Islam et al.*, 2007; *Viviroli et al.*, 2007] assessed water stress by comparing water availability and water demand on a yearly time scale, mainly by using macroscale hydrological models. On the basis of these assessments, regions with present and future water stress were identified. Annual assessments, however, potentially underestimate the intensity of water stress since within-year variations of water stress are not taken into account. Such variations can be brought on by increased demand, for example in ever-expanding urban centers, by a temporary rise in demand, for example increased irrigation demand during droughts, and by untimely availability, for example, in the monsoon-dominated areas of (sub) tropical Asia, where 80% of the average annual discharge is concentrated in the summer period because of the coincidence of the snowmelt and the peak in rainfall [*Shiklomanov*, 1993].

[3] Expanding on existing annual assessments this study reveals a new dimension of water stress by using a finer, monthly, temporal scale and by explicitly incorporating nonrenewable groundwater abstraction as a particular water resource. The first paper of this series [*van Beek et al.*, 2011] described the global hydrological model PCR-GLOBWB [*van Beek and Bierkens*, 2009] and the prospective reservoir scheme that were used to simulate monthly time series of blue water (i.e., surface fresh water) and green water (i.e., soil water) availability for the years 1958–2001. In this second paper, global blue water demand is calculated comprising that of the agricultural (i.e., irrigation and livestock), industrial and domestic sectors, using the latest available global data sets (e.g., population, livestock densities and irrigated areas; see Figure 1), all aggregated to the same spatial reso-

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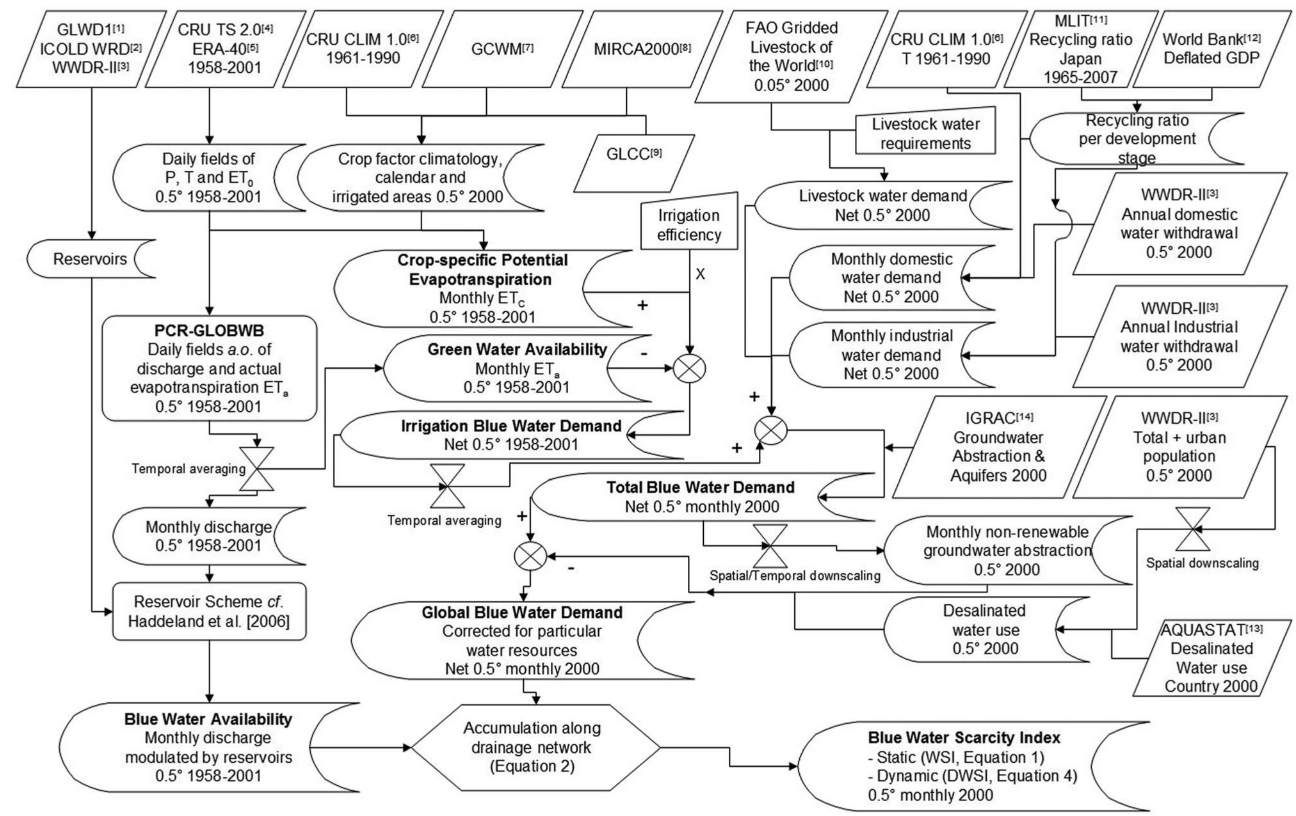

Figure 1. Flowchart of dependencies between data sources and computation of the water scarcity index. Sources indicated in the flowchart are as follows: 1, *Lehner and Döll* [2004]; 2, *International Commission on Large Dams* [2003]; 3, World Water Assessment Programme (WWDR-II, http://wwdrii.sr.unh.edu/); 4, *Mitchell and Jones* [2005]; 5, *Kållberg et al.* [2005]; 6, *New et al.* [1999]; 7, *Siebert and Döll* [2008]; 8, *Portmann et al.* [2008]; 9, EROS, USGS (Global land cover characteristics data base, version 2.0, http://edcdaac.usgs.gov/glcc/globedoc2_0.html); 10, Food and Agriculture Organization of the United Nations (http://www.fao.org/ag/AGAinfo/resources/en/glw/GLW_dens.html) and Environmental Research Group Oxford (http://ergodd.zoo.ox.ac.uk/); 11, *MLIT* [2007]; 12, *World Bank* [2006, 2007; country classification, http://web.worldbank.org]; 13, FAO AQUASTAT database (http://www.fao.org/nr/water/aquastat/data/); 14, International Groundwater Resources Assessment Centre (http://www.igrac.nl/).

lution of 0.5°. Here, blue water demand is defined as net blue water demand, the potential consumptive use from available resources (see Table 1 for an overview of terms and their respective components). Consequently, it is lower than the gross blue water demand as water withdrawn for industrial and domestic use is recycled and returned to the surface water while part of the gross irrigation water demand is met by green water availability [cf. *Rost et al.*, 2008]. Use of the net blue water demand consequently leads to an optimistic assessment of water stress yet can be defended on the grounds that the return flow of water in is fairly constant and that the losses by evapotranspiration in irrigation constitute a large amount of the overall water demand, be it gross or net. Thus, net blue water demand may be used to estimate the consumptive water use, as proposed by *Döll and Siebert* [2002], although actual consumption may be lower as a result of

Table 1. List of Terms and Components Considered

	Required to Satisfy Needs	Actually Available to Satisfy Needs
Gross (considering all water requirements)	Gross demand. (1) Irrigation: evapotranspiration (blue and green water) and transport losses. Livestock. (2) Domestic: blue water consumption and return flow. (3) Industrial: blue water consumption and return flow.	Withdrawal. (1) Irrigation: evapotranspiration (blue only), transport losses, and livestock. (2) Domestic: blue water consumption and return flow. (3) Industrial: blue water consumption and return flow.
Net (consumptive blue water requirements only)	Net demand. (1) Irrigation: evapotranspiration (blue only), transport losses, and livestock. (2) Domestic: blue water consumption. (3) Industrial: blue water consumption.	Consumptive water use [cf. *Döll and Siebert*, 2002]. (1) Irrigation: evapotranspiration (blue only), transport losses, and livestock. (2) Domestic: blue water consumption. (3) Industrial: blue water consumption.

physical, technological or socioeconomic limitations. Also, we explicitly quantified the amount of water made available through desalination and nonrenewable groundwater abstraction that decreases the demand for blue water. In order to make use of the best available data and to make our assessment as relevant for the present-day situation as possible, we opted for the year 2000 as benchmark while the long-term climate variability is characterized by the 44 year period from 1958 until 2001. Thus, irrigation water demand is computed for the irrigated areas of the year 2000 but with inclusion of the long-term climatic variability in green water availability over the period 1958–2001 [see *van Beek et al.*, 2011, section 2.1]. Monthly livestock, industrial and domestic water demand are estimated for the year 2000 and constant between years. Total blue water demand is thus the sum of the climate-driven irrigation water demand for each year of 1958–2001 and the other sectoral demands of the year 2000. Per month, total blue water demand is confronted with the blue water availability over the period 1958–2001 to obtain a 44 year monthly time series, i.e., 528 maps, of global blue water stress, thus reflecting long-term climate variability only. The inclusion of long-term blue water availability sets this study apart from that of *Hanasaki et al.* [2008a, 2008b] who assessed temporal variations in global water stress in a comparable manner albeit at a lower spatial resolution (1° × 1°) and for a shorter period of 10 years (1986–1995). Moreover, this study has a finer spatial and temporal resolution as it takes spatial variations in the recycling ratio of the domestic and industrial sectors into account and it considers a monthly climatology of domestic water demand and monthly variations in the use of particular resources, including the alleviating role of nonrenewable groundwater abstraction which is evaluated globally for the first time.

[4] Blue water stress is defined in terms of the commonly used water scarcity index (WSI) of *Falkenmark* [1989]. This static water stress is calculated on a monthly and an annual basis over the total period of 1958–2001. The detrimental effect of recurring and persistent water stress is captured by the DWSI, conform to *Porporato et al.* [2001] for situations corresponding to severe water stress. In a limited validation exercise for this assessment, the water stress over the past 44 years reflecting the climate variability only, thus neglecting the changes in past water demand, is compared with observed water shortage (i.e., drought) in several developed, emerging and developing countries such as the Netherlands, Japan, Malaysia, the Philippines, Afghanistan, Pakistan, Zimbabwe and the state of Virginia (United States).

2. Methods

2.1. Definition of Water Stress

[5] Water stress occurs when different types of water demand compete for the same scarce water resources. *Falkenmark* [1989] defined the WSI that compares water demand with water availability:

$$\mathrm{WSI} = \frac{D}{A}, \tag{1}$$

where WSI is the water scarcity index, D is the total water demand and A is the total water availability ($\mathrm{m}^3\ \mathrm{month}^{-1}$). This study uses monthly averages of demand and availability.

[6] The WSI essentially expresses how much of the available water is taken up by the demand. *Falkenmark et al.* [2007] delineated looming water scarcity and actual scarcity between $0.2 \leq \mathrm{WSI} < 0.4$ and $\mathrm{WSI} \geq 0.4$, respectively. These domains correspond to the conditions of moderate to severe water stress of *Kundzewicz et al.* [2007], with water availability per capita ranging between 1700 and 1000 $\mathrm{m}^3\ \mathrm{yr}^{-1}$. According to these authors, very high stress or economically debilitating water stress occurs at water availabilities below 500 $\mathrm{m}^3\ \mathrm{yr}^{-1}$ per capita or water scarcity indices above 0.8.

[7] In this study, water availability corresponds to blue water availability, Q ($10^6\ \mathrm{m}^3\ \mathrm{month}^{-1}$), consisting of the locally generated runoff and any remaining upstream discharge after evaluation of the prognostic reservoir operation scheme [see *van Beek et al.*, 2011, section 2.4] and the deduction of the upstream local water consumption (see also Figure 1):

$$Q_i = Q_{loc\,i} + \sum_{j=i+1}^{n} \left(Q_j - D_j\right), \tag{2}$$

where Q is the total discharge, Q_{loc} is the specific discharge or local runoff, D is the local net blue water demand, taken to be the local water consumption [*Döll and Siebert*, 2002] (all in $10^6\ \mathrm{m}^3\ \mathrm{month}^{-1}$). Subscript i denotes the cell under consideration and $j = i + 1, \ldots, n$ all cells upstream from this point.

[8] The summation in Equation returns no upstream water for the cell under consideration whenever the available discharge is less than the local water consumption (i.e., net blue water demand). Otherwise, the discharge in excess of the local water consumption is accumulated along the drainage network. Water demand includes the demand of the industrial and the domestic sector, corrected with the recycling ratio if appropriate (sections 2.2.3 and 2.2.4), and the agricultural sector (sections 2.2.1 and 2.2.2; see also Figure 1). The agricultural water demand is broken down into the livestock and the irrigation water demand, the latter being the amount of water required to satisfy the crop-specific potential transpiration with inclusion of any additional losses during transport or application but after deduction of the available green water, i.e., the soil moisture available to transpiration under nonirrigated conditions. In several regions of the world part of water demand is met from desalination and/or the abstraction of nonrenewable groundwater resources (section 2.4). Therefore, the volume of desalinated water and abstracted nonrenewable groundwater is subtracted from the water demand prior to the calculation of the WSI (equation (1)).

[9] Over the period 1958–2001 the WSI is calculated on an annual basis as done in previous studies [e.g., *Vörösmarty et al.*, 2000] and on a monthly basis. The monthly values are subsequently degraded to annual values to evaluate the effect of temporal resolution on the identification of problem regions. To identify regions that are significantly different over the simulation period, we use a difference of means test on a cell-by-cell basis to calculate the Student's t statistic:

$$t = \frac{\overline{\mathrm{WSI}}_a - \overline{\mathrm{WSI}}_m}{\sqrt{\frac{s^2_{\mathrm{WSI}_a}}{n-1} + \frac{s^2_{\mathrm{WSI}_m}}{n-1}}}, \tag{3}$$

where $\overline{\mathrm{WSI}}$ is the mean WSI based on the annual and the monthly assessments (subscripts a and m, respectively). Likewise, s_{WSI} denotes the standard deviation, which is cal-

Table 2. Population and Water Withdrawal by Sector per Continent and Classified by GDP per Capita for the Year 2000[a]

	Population in 2000 (millions)	Total Freshwater Withdrawal (km^3 yr^{-1})	Per Capita Withdrawal (m^3 capita^{-1} yr^{-1})	Withdrawal per Sector (%)		
				Agriculture	Industry	Domestic[b]
Continents						
Africa	818.7	213.2	260.4	83.1	4.3	12.6
Asia	3679.8	2294.8	623.6	84.9	7.2	7.9
Europe	729.2	392.2	537.8	29.3	48.5	22.2
North America	476.1	622.5	1307.5	44.1	33.9	22.0
South America	341.2	164.6	482.4	84.8	6.4	8.8
Oceania	28.7	26.3	916.4	64.9	10.4	24.7
GDP per capita classes[c]						
Low income countries[d]	2203.2	1288.2	584.7	86.0	7.7	6.3
Middle income countries[e]	2961.7	1549.4	523.2	69.0	16.1	14.9
High income countries[f]	908.8	875.7	963.6	39.6	39.4	21.0
Global	6073.7	3713.7	611.4	68.6	18.1	13.3

[a]These data are based on FAO AQUASTAT, the work of *Gleick et al.* [2006], and the Pacific Institute's The World's Water Web site (http://www.worldwater.org/data.html).
[b]Domestic sector, comprising households and municipalities.
[c]GDP per capita is based on the year 2000/2001 (year 2000 U.S. dollars, World Bank).
[d]GDP per capita of low income countries is less than US$755, and the average GDP per capita of these countries is US$359.
[e]GDP per capita of middle income countries is between US$756 and US$9265, and the average GDP per capita of these countries is US$2843.
[f]GDP per capita of high income countries is more than US$9266, and the average GDP per capita of these countries is US$21,880.

culated from the $n = 44$ averaged annual values in the case of the monthly assessment. The degrees of freedom were estimated for each cell assuming different standard deviations and the two-tailed probability of equality of means returned.

[10] In addition to the WSI, a compound statistic is calculated from the monthly time series combining the mean duration and the frequency of water scarcity with the severity of the water stress. This statistic is based on that of *Porporato et al.* [2001] developed to quantify the effect of prolonged or recurring droughts for vegetation [e.g., *Brolsma and Bierkens*, 2007]:

$$\mathrm{DWSI} = \left(\frac{\overline{\xi_s}\,\overline{T_s}}{kT}\right)^{1/\sqrt{f_s}}, \tag{4}$$

where DWSI is the dynamic water stress index, $\overline{\xi_s}$ is the average water stress over a period of continuous stress that is counteracted by the resilience parameter k (both dimensionless). $\overline{T_s}$ is the mean duration of a stress period (months), T is the length of the growing season under consideration (months) and f_s is the frequency of recurring stress periods. Damage increases when the stress exceeds the resilience, when the stress persists over a longer period or when the stress occurs more frequently. This relationship is nonlinear with frequency being more damaging under low-stress conditions but duration being dominant under high-stress conditions. In this study we evaluate the DWSI, for an average year (T = 12 months) and assume water stress to occur whenever the monthly water scarcity index ≥ 0.4. For k, we adopt the lower limit at which water stress limits economic development (WSI = 0.8), reduced by the threshold of 0.4 denoting the onset of water stress. Hence, $\overline{\xi_s}/k = (\overline{\mathrm{WSI} \geq 0.4})/(0.8 - 0.4)$. The frequency and the mean duration are calculated from the total number of stress periods over the 44 year period and the total number of months that the threshold is exceeded, respectively.

2.2. Water Demand

[11] In most countries of the world, water withdrawal and consumption have increased over the last decades because of demographic and economic growth, changes in lifestyle, and expanded water supply systems [*Kundzewicz et al.*, 2007]. Table 2 shows the statistics of population and water withdrawal by sectors (%) by continent and GDP per capita classes in the year 2000. Industrial and domestic water withdrawals are about 18% and 13% of total water withdrawal, respectively. Agricultural water withdrawal amounts to nearly 70% of total water withdrawal and is by far the largest among the three sectors. Water withdrawal and socioeconomic data were collected from various sources as shown in Figure 1. All data are specified per month for the year 2000 and gridded at 0.5°. In this study, gross water demand is subsequently reduced to net blue water demand by considering green water availability for irrigation and recycling ratios for the industrial and the domestic sector. Sections 2.2.1–2.2.4 describe the methodologies used in this study to compute net blue water demand for the agricultural (i.e., livestock and irrigation), the industrial, and the domestic (i.e., households and municipalities) sectors.

2.2.1. Livestock Water Demand

[12] The amount of water used by livestock is very small (i.e., less than 1–2% of total water demand) in most countries compared to the other sectors. However, livestock water demand may be considerable if irrigation water demand is low [*Flörke and Alcamo*, 2004]. Livestock water demand was computed from the grid-based distribution at 0.05° of six major types of livestock and their water consumption rate, following the method of *Alcamo et al.* [2003a] (Figure 1). It is assumed that all water withdrawals for livestock are fully consumed [*Alcamo et al.*, 2003a; *Flörke and Alcamo*, 2004] and we therefore equate net with gross blue water demand. We obtained the gridded data of global livestock density of cattle, buffalo, sheep, goats, pigs and poultry in the year 2000 from *Wint and Robinson* [2007]. We then multiplied the number of livestock in each grid cell by their specific daily water consumption [*Alcamo et al.*, 1997] to estimate daily livestock water demand. This value was summed to monthly values under the assumption that livestock water consumption is constant over the year.

2.2.2. Irrigation Water Demand

[13] Irrigation is particularly important among all the sectors as its water withdrawal comprises nearly 70% of the total [*Shiklomanov*, 2000a] (see Table 2). Importantly, irrigation water demand has a large seasonal variability because of the various growing seasons of different crops and varies spatially depending on cropping practices and climatic conditions. *Döll and Siebert* [2002] estimated irrigation water requirements by using the CROPWAT method [*Smith*, 1992] based on the CRU data set of meteorological conditions provided by *New et al.* [2000]. *Flörke and Alcamo* [2004] and *Hanasaki et al.* [2006] used similar methods to estimate irrigation water demand. They simulated the crop calendar to estimate the amount of irrigation water required for paddy (rice) and nonpaddy crop types. This estimation method heavily relies on precipitation and temperature as irrigation is assumed to be applied under optimal climate conditions only. This may be inaccurate for water scarcity may lead farmers to irrigate under less than optimal climate conditions [*Döll and Siebert*, 2002].

[14] This study used the latest available data set of monthly irrigated areas and crop calendars for 26 crops around the year 2000 (MIRCA2000 [*Portmann et al.*, 2008, 2010]). This data set includes monthly cropping patterns and monthly cropping calendars for 26 major irrigated crops on the global scale with a spatial resolution of 5 min. For both variables, the main crop and up to nine subcrops are specified that may represent multicropping systems, varieties of the same crop growing in different seasons in different areas of the grid cell, or different specific crops included in crop groups [*Portmann et al.*, 2008, so rice is grown more than once a year in the same field in many regions of the world as part of multicropping systems. The corresponding crop development stages, crop factors and effective rooting depth for each crop are given by the GCWM data set of *Siebert and Döll* [2008, Table 2]. We blended the values with the crop factors used in PCR-GLOBWB. First, we aggregated the monthly crop factors and the irrigated areas of the 26 crops to one monthly value for each 0.5° cell (see also Figure 1). These were then substituted for those calculated from the GLCC data set (Earth Resources Observation and Science Center (EROS), U.S. Geological Survey (USGS), Global land cover characteristics data base, version 2.0, http://edcdaac.usgs.gov/glcc/globedoc2_0.html, accessed 2002) and the fraction irrigated areas updated in the calculation of the effective values for short and tall vegetation [see *van Beek et al.*, 2011, section 2.1]. When the fraction of the irrigated areas specified was larger than that of the GLCC data set, it was expanded first at the expense of rain-fed agriculture, then at that of natural vegetation. If the fraction irrigated areas was smaller than that specified in the GLCC, rain-fed agriculture and natural vegetation were increased proportionally.

[15] Irrigation blue water demand was calculated for each 0.5° cell by using the simulated potential and actual evapotranspiration from PCR-GLOBWB (see equations (1), (3), (4), and (6) of *van Beek et al.* [2011, section 2.2]). Crop-specific potential evapotranspiration for the irrigated areas is calculated from the effective crop factor at 0.5° for the 26 irrigated crop types represented by MIRCA2000 [*Portmann et al.*, 2008, 2010] and the reference potential evapotranspiration. Taking the simulated actual transpiration under nonirrigated conditions from PCR-GLOBWB as green water availability, the crop-specific transpiration that has to be met by irrigation to ensure optimum growth, $D_{Irr_{crop}}$ (m d^{-1}), is given by

$$D_{Irr_{crop}} = T'_c - T'_a, \tag{5}$$

where the primed variables T'_c and T'_a denote the crop-specific potential and actual transpiration for the irrigated areas, respectively (all in m d^{-1}), which may differ from the overall cell values used in PCR-GLOBWB.

[16] The actual transpiration for the irrigated areas, T'_a, may differ from that obtained from PCR-GLOBWB, T_a, as crops tend to have shallower rooting systems, especially under irrigated conditions [*Siebert and Döll*, 2010]. Thus, the actual transpiration for the irrigated areas is estimated by

$$T'_a = T'_c \sum \left(r'_i \frac{T_{a_i}}{T_{c_i}} \right), \tag{6}$$

where T_c and T_a correspond to the overall cell values of potential and actual transpiration for the two land cover types (short, tall) of PCR-GLOBWB (all in m d^{-1}) and the subscript i, denotes the two soil layers present. Primed variables denote the values over the irrigated area where r'_i is the root fraction obtained from the effective rooting depth of each irrigated crop in a 0.5° cell, assuming an exponential root distribution with depth [*Jackson et al.*, 1996].

[17] To account for losses during application we included the additional loss of bare soil evaporation ($ES_0 - ES_a$) over the irrigated areas and multiplied the required irrigation water with a dimensionless efficiency factor, e_{Irr} [*Flörke and Alcamo*, 2004] to obtain the total net irrigation blue water demand, $D_{Irr\ tot}$ (m d^{-1}):

$$D_{Irr_{tot}} = e_{Irr}\left[D_{Irr_{crop}} + (\mathrm{ES}_0 - \mathrm{ES}_a)\right]. \tag{7}$$

The potential bare soil evaporation, ES_0, and the actual bare soil evaporation, ES_a, were simulated by PCR-GLOBWB (all in m d^{-1}) [see *van Beek et al.*, 2011, section 2.2]. The efficiency factor takes into account that additional water is lost to evaporation during transport and water in excess of the demand has to be applied to prevent salinization. In general, about half of the water diverted for irrigation is consumed through evapotranspiration [*Jackson et al.*, 2001]. However, some of irrigation water is returned to the available blue water resources and we applied here a single efficiency factor of 1.2, i.e., 20% more irrigation water is needed to account for additional evaporative losses during transport and application, without explicitly taking the return flow into account. Moreover, we did not consider any evaporative losses by canopy interception as most irrigation is applied by flooding.

2.2.3. Industrial Water Demand and Recycling Ratio

[18] Industrial water withdrawal often amounts to more than a half of total water withdrawal in developed (i.e., industrialized) countries. According to *Gleick et al.* [2006], the ratio of industrial to total water withdrawal in Finland, United Kingdom, France, Canada and Russian is 84%, 75%, 74%, 69%, and 64%, respectively. Industrial water withdrawals were taken from the WWDR-II data set [*Shiklomanov*, 1997; *World Resources Institute*, 1998; *Vörösmarty et al.*, 2005] and assumed to be constant over the year, similar to the study of *Hanasaki et al.* [2006].

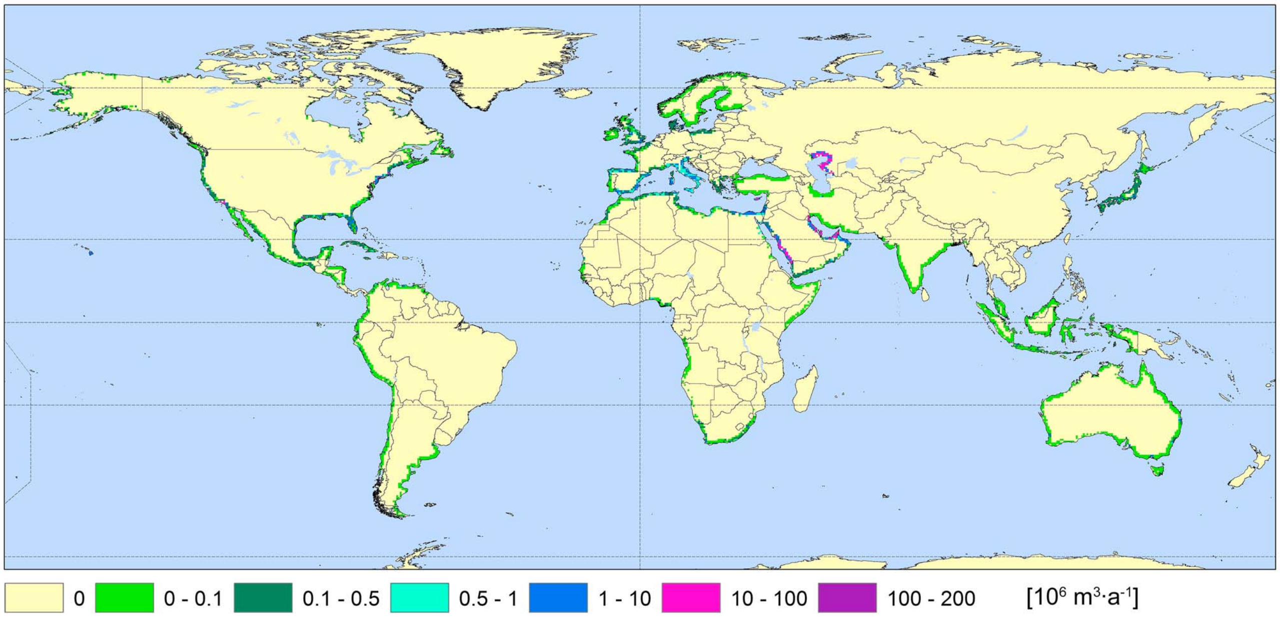

Figure 2. Total desalinated water use for the year 2000.

[19] A large amount of industrial water is used for cooling of thermal and nuclear power generation and returned to the river after use [*Shiklomanov*, 2000b] and most of the industrial water is recycled or reused, especially in developed countries (e.g., Japan). *Oki et al.* [2001] suggested that the recycling ratio for industry is 86%. Later, *Oki and Kanae* [2006] indicated that nearly 80% of water withdrawn for the industrial sector in Japan is currently recycled [*Ministry of Land, Infrastructure, and Transport in Japan* (*MLIT*), 2007]. The recycling ratio is considered as high as the one for Japan in other developed countries.

[20] Because of a lack of data, we generalized the recycling ratio for other countries on the basis of the historical development of the recycling ratio of Japan (1965–2007; see also Figure 1). The ratio was obtained from Japanese Ministry of Land, Infrastructure and Transport [*MLIT*, 2007]. On the basis of their Gross Domestic Product (GDP) per capita, we classified countries into three groups of economic development [*World Bank*, 2006; World Bank, country classification, http://data.worldbank.org/about/country-classifications, accessed 2006]: (1) developing (i.e., low income) economies, (2) emerging (i.e., middle income) economies and developed (i.e., high income) economies (see Table 2). Equally, we classified the historical development of Japan on the same grounds, using indexed data for 2000 considering deflation (GDP deflator [*World Bank*, 2006, 2007]) and averaged the recycling ratio for each development stage, respectively 40%, 65% and 80%. China is classified as an emerging country and its recycling ratio of about 60 to 65% for 2004 (Ministry of Water Resources of China, http://www.mwr.gov.cn/english/) agrees well with the estimate obtained from Japan.

[21] To estimate the net industrial water demand, gross industrial water demand data of the WWDR-II were multiplied with the complement of the generalized recycling ratio of each country (60%, 35%, or 20%). If there were no GDP data available, the original gross demand was used without reduction to emphasize the detrimental effect of untreated spillage on water availability.

2.2.4. Domestic Water Demand

[22] Domestic water demand is a complex function of socioeconomic and climatic factors as well as public water policies and strategies [*Babel et al.*, 2007]. We evaluated annual courses or monthly fluctuations in domestic water demand for selected countries representing a wide range of environmental and socioeconomic conditions: Japan [*MLIT*, 2007], Spain [*Martinez-Espiñeira*, 2002], Australia [*Loh and Coghlan*, 2003], Iran [*Mahvi and Norouzi*, 2005], and Nigeria [*Nyong and Kanaroglou*, 1999]. In general, there is a higher demand in summer, when water availability may be at its ebb. Therefore, monthly domestic water demand was estimated as a function of temperature:

$$W_{Dom\,m} = \frac{W_{Dom\,a}}{12}\left[\left(\frac{T - T_{avg}}{T_{\max} - T_{\min}} R_{Dom}\right) + 1.0\right], \tag{8}$$

where W_{Dom} is the domestic water withdrawal (10^6 m^3) based on the WWDR-II [*Vörösmarty et al.*, 2005]. Subscripts m and a denote month and year, respectively. T, T_{Avg}, $T_{\min}$, and $T_{\max}$ are the monthly temperature and the average, minimum, and maximum temperature over the year, respectively (all in °C), as obtained from the CRU climatology (1961–1990) [*New et al.*, 1999]. R_{Dom} is the amplitude (dimensionless), the relative difference in domestic water demand between the months with the warmest and the coldest temperatures. Here we used a value of 10% or 0.1 that fitted the small variations in Japan and Spain and the near-constant values for tropical Nigeria best.

[23] Identical to the industrial sector, a substantial part of water withdrawn for domestic sector is returned, purified or not, to the river network [*Shiklomanov*, 2000b] (see also Figure 1). This fraction largely depends on a presence and an advancement of the sewer system. To quantify the net water demand for the domestic sector, we applied the same

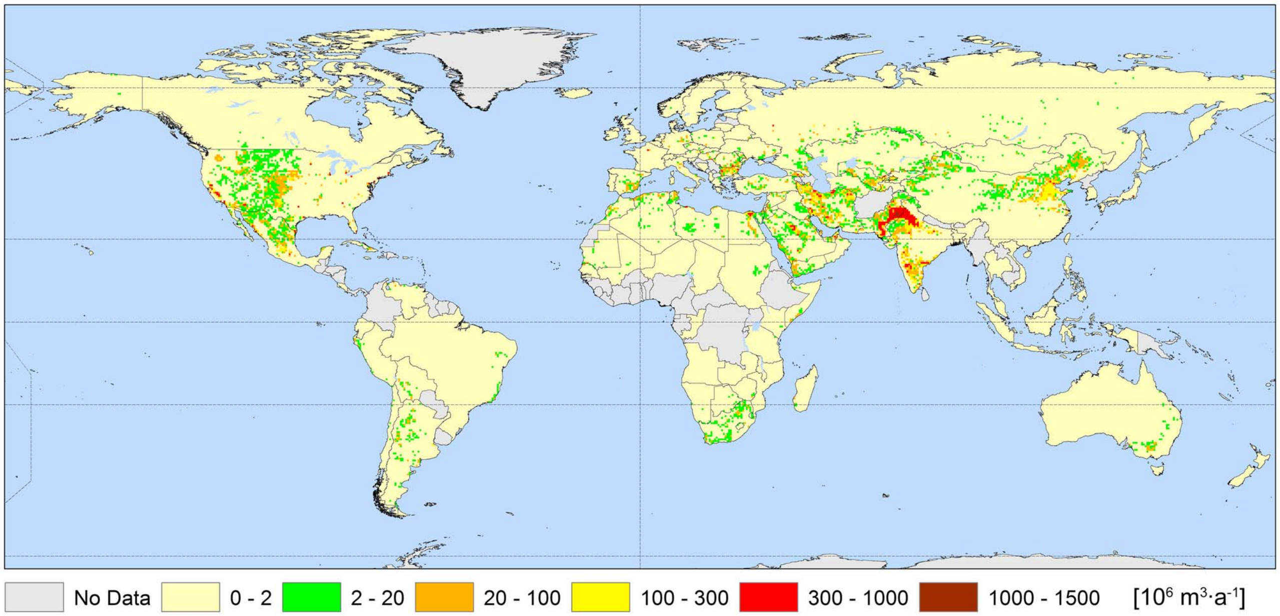

Figure 3. Nonrenewable groundwater abstraction for the year 2000 [after *Wada et al.*, 2010].

recycling ratio as estimated for the industrial sector but multiplied it with the fraction of the urban population that was assumed to be connected to the sewer system:

$$D_{Dom\,m} = W_{Dom\,m}\left[1 - \left(F_{urban}R_{Industry}\right)\right], \tag{9}$$

where D_{Dom} is the net domestic water demand (10^6 m^3), F_{urban} is the fraction of urban to total population (dimensionless) and $R_{Industry}$ is the recycling ratio derived for the industrial sector (dimensionless).

2.3. Desalinated Water Use

[24] The amount of water from particular resources (i.e., desalinated water use and groundwater abstraction; Figure 1) can be extremely important in regions where surface water is scarce in quantity or quality. Desalinated water, for example, is drawn from oceans and used in many desert regions of the world (e.g., the Middle East), its volume increasing each year. We obtained the latest data of desalinated water use from the FAO AQUASTAT database. According to FAO AQUASTAT, the total amount of desalinated water use was around 4.6 km^3 yr^{-1} in the year 2000. Kazakhstan used the largest amount, around 1.3 km^3 yr^{-1}. Population data of the WWDR-II [*Elvidge et al.*, 1997a, 1997b; *Environmental Systems Research Institute*, 1993; *Tobler et al.*, 1995] were used to downscale the country statistics. We weighed desalination by the population density in a ribbon up to 40 km from the coast as this population has ready access to desalinated water. Desalinated water use was assumed to be constant over the year (Figure 2). Desalinated water use was eventually subtracted from the blue water demand as this alleviates the demand that has to be met from the available surface fresh water.

2.4. Nonrenewable Groundwater Abstraction

[25] Groundwater is in demand all over the world because of its high quality or to supply water when surface water is scarce or absent altogether. On the global scale groundwater satisfies 40% of the need of self-supplied industry, 20% of the irrigation water demand and 50% of the demand of drinking water supply [*Zektser and Everett*, 2004]. Global groundwater abstraction was obtained from the GGIS (Global Groundwater Information System) of IGRAC (International Groundwater Resources Assessment Centre, http://www.igrac.net/) as annual groundwater abstraction in m^3 per capita per country and for major groundwater regions of the world. The data is not available in Afghanistan, Myanmar, Nepal, Sri Lanka, North Korea, the former Yugoslavia and several countries in Africa and South America where no groundwater abstraction rates have been reported in GGIS. Groundwater abstraction was indexed for the year 2000 on the basis of population. Annual groundwater abstraction was then spatially downscaled into 0.5° by using an intensity of the annual total water demand per cell over a country. Groundwater abstraction was subsequently disaggregated into monthly values on the basis of the monthly total water demand. For both desalinated water use and groundwater abstraction, country statistics were weighed by extent whenever multiple countries were present in a 0.5° cell (i.e., up to four countries in one grid cell in this study).

[26] Importantly, if the groundwater that is abstracted is renewable, i.e., smaller than the groundwater recharge, it has no bearing on the water stress analysis. This, because water thus abstracted will only decrease the base flow to the river (simulated by PCR-GLOBWB), and it makes no difference if this water is available from surface water or by abstraction. However, the amount of groundwater that is abstracted in excess of groundwater recharge will, albeit temporally and nonrenewably, decrease the demand for blue water or river discharge [*Wada et al.*, 2010]. As we aim to assess the *blue* water stress, the nonrenewable groundwater abstraction is subtracted from the total water demand. Figure 3, as taken from *Wada et al.* [2010], shows the nonrenewable groundwater abstraction (10^6 m^3 yr^{-1}) calculated by subtracting the

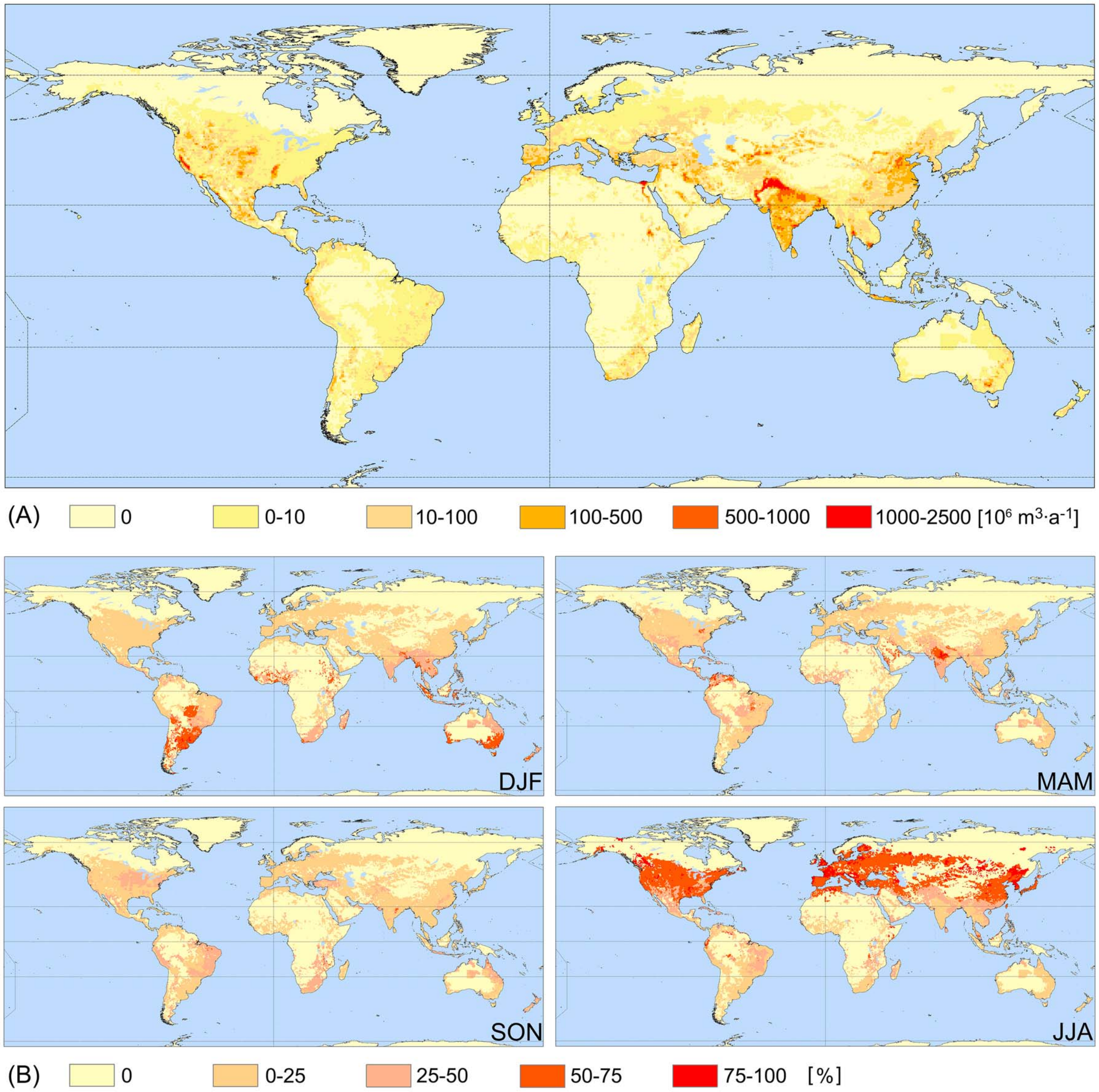

Figure 4. (a) Annual total net irrigation water demand and (b) relative seasonal distribution over the period 1958–2001 (clockwise from the top left: DJF, December-January-February; MAM, March-April-May; JJA, June-July-August; SON, September-October-November).

natural groundwater recharge (10^6 m^3 yr^{-1}) as simulated by PCR-GLOBWB from the groundwater abstraction (10^6 m^3 yr^{-1}). The global nonrenewable groundwater abstraction is 309 km^3 yr^{-1}, which is 42% of the total groundwater abstraction of 734 km^3 yr^{-1}. Nonrenewable groundwater abstraction is particularly large in NW and southern India, NE Pakistan, NE China, central and western United States, Mexico, southern Spain and northern Iran. This study thus identifies the regions that are currently under diminished water stress, but where water stress can be expected to increase in the near future when groundwater aquifers become unattainable (i.e., groundwater levels fall too deep).

3. Results

3.1. Irrigation Water Demand

[27] To place our results in the context of existing water scarcity studies we start by comparing our estimated irrigation water demand with previous studies. We estimate the global annual amount of irrigation water required to satisfy the additional crop-specific transpiration ($D_{Irr_{crop}}$, equation (5)) to be 1176 km^3 yr^{-1} on average over the period 1958–2001, while that required to meet the total net irrigation blue water demand ($D_{Irr\ tot}$, equation (7)) amounts to 2057 km^3 yr^{-1}; spatial distribution and seasonal variations are shown in Figure 4. These results compare well with those of *Döll and Siebert* [2002], *Hanasaki et al.* [2006], *Rost et al.* [2008], and *Wisser et al.* [2008], who estimated these values ranging from 1092 to 1364 km^3 yr^{-1} and from 2254 to 3100 km^3 yr^{-1}. Because of the inclusion of additional losses, total net irrigation water demand is larger than the estimated vapor flux over irrigated areas of 1800 km^3 yr^{-1} by *Shiklomanov* [2000b] but lower than the estimate of 3100 km^3 yr^{-1} by *Wisser et al.* [2008] that is based on the same climatology and irrigated areas but considered higher losses because of irrigation efficiency (between 1.4 and 2.8 [cf. *Döll*

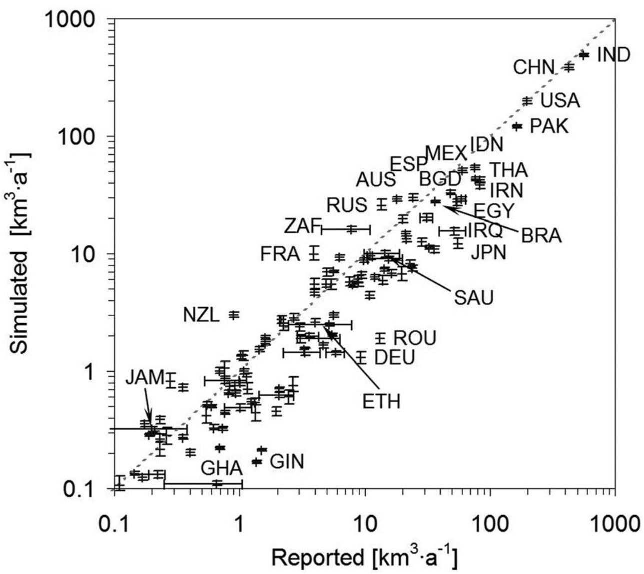

Figure 5. Comparison between simulated net blue water demand for livestock and irrigation (*y* axis) and reported agricultural water withdrawals (*x* axis) per country. Reported values are taken from the FAO AQUASTAT database over the period 1998–2002. *X* error bars are based on the estimated agricultural water withdrawal for 90 developing countries by FAO compared to the observed value reported to the AQUASTAT database [*Food and Agriculture Organization*, 2008]. Simulated values are representative for the year 2000. *Y* error bars are based on the range in net irrigation blue water demand due to variations in green water availability over the simulation period 1958–2001. Selected countries are identified by their ISO country codes.

and Siebert, 2002]). According to the FAO AQUASTAT database, the annual agricultural water withdrawal was 2483 km^3 yr^{-1} for 2002. Figure 5 compares per country the annual agricultural water withdrawal as reported by the FAO AQUASTAT database with the sum of the computed livestock and irrigation water demand. Overall, the correlation between the reported and simulated values is high (R^2 = 0.98) and good results were obtained for the largest users of irrigation water (i.e., India, China, and the United States). However, overall the simulated values are 15% lower than the reported ones. Underestimation is particularly large for countries with paddy cultivation (e.g., Indonesia, Thailand, and Japan) for which the efficiency factor of 1.2 may be too optimistic and multiple cropping calendars very uncertain and for countries for which total irrigated area estimates are poor (e.g., Iraq, Iran, and Egypt). In addition, the reported withdrawals generally exceed the simulated blue water demand as the latter does not explicitly consider return flow. Overestimation occurs for more developed countries that may not exploit the irrigated areas fully (e.g., Russia) or where irrigation is more efficient (e.g., New Zealand, France, and Australia). Also, the reported totals are those of agricultural water withdrawals and the inclusion of livestock water withdrawal may constitute another source of error (e.g., Germany and Romania). As indicated by the *Y* error bars and as observed by *Wisser et al.* [2008] the interannual variability in irrigation water demand is relatively small (coefficient of variation less than 10%). In contrast, estimates of irrigation water withdrawal are very uncertain for want of reliable national statistics and more points fall within the uncertainty band around the 1:1 line (e.g., Jamaica and Ethiopia).

3.2. Static Water Stress

[28] Table 3 compares our estimate of water stress with those of other authors [e.g., *Arnell*, 1999, 2004; *Alcamo et al.*, 2000, 2003b; *Vörösmarty et al.*, 2000; *International Water Management Institute*, 2000; *Oki et al.*, 2001, 2006; *Islam et al.*, 2007] in terms of global population exposed to different degrees of blue water stress. Estimates vary considerably depending on the spatial resolution (i.e., country, watershed, or grid based). Country-based estimates generally return lower values for the population under water stress compared to watershed and grid-based estimates as they hide substantial within-country variation of water availability and demand [*Arnell*, 2004]. Previous watershed and grid-based estimates of the population under severe water stress range from 1.2 to 2.7 billion when based on annual totals of water availability and demand. In comparison, we estimate the total global population in the year 2000 experiencing severe water stress to be 1.1 billion while 0.6 billion experience moderate water stress. This estimate on annual totals is close to the one by *Islam et al.* [2007] for the same benchmark year. However, the total population under severe water stress is lower for our study than for any other study except the country-based estimates. Besides differences in blue water availability arising from variations in simulated runoff [*van Beek et al.*, 2011, Table 6] and the inclusion of upstream local water consumption not taken into account in other studies [e.g., *Oki et al.*, 2001], the main reason for the observed difference is a lower water demand. This study applied a recycling ratio to the industrial and the domestic sector to account return flow and considered green water availability in the definition of irrigation water demand, thus defining this assessment in terms of net rather than gross blue water demand. In addition, this study considered the additional availability of the desalinated water use and the nonrenewable groundwater abstraction which was subtracted from the total water demand as our objective is to assess *current* blue water stress as described in the sections 2.3 and 2.4.

[29] When based on the monthly averaged, climate-induced water stress over the period 1958–2001, the total global population in the year 2000 experiencing severe water stress is estimated to be 1.7 billion while 0.8 billion experience moderate water stress. These figures are more than 40% higher than those based on the annual totals as seasonal and interannual variability in availability are taken into account in case of the irrigation water demand and the domestic water demand. Figure 6 shows the global distribution of areas experiencing different degrees of water stress based on the annual and the monthly totals of water availability and water demand (Figures 6a and 6b). In addition, a comparison is made between the assessments at different temporal resolutions by means of the *t* test of equation (3) (Figure 6c). Compared to conventional assessments on an annual basis, this test shows a clear increase in water stress (see Table 3), as also observed by *Hanasaki et al.* [2008b] in a recent assessment of water stress at a fine temporal scale

Table 3. Global Assessments of World Population Experiencing Blue Water Stress[a]

	Degrees of Water Stress							
	No Stress	Low Stress	Moderate Stress	Severe Stress	Total	Year[b]	Spatial Resolution	Temporal Resolution[c]
Per capita water availability (m^3 $capita^{-1}$ yr^{-1})	>1700	-	1700–1000	<1,000				
Water scarcity index	WSI < 0.1	0.1 ≤ WSI < 0.2	0.2 ≤ WSI < 0.4	0.4 ≤ WSI				
WMO [1997]	1.7 (30%)	2.1 (37%)	1.4 (25%)	0.5 (9%)	5.7	1995	Country	Annual
Arnell [1999]	-	-	1.4 (27%)	0.4 (8%)	5.2	1990	Country	Annual
Vörösmarty et al. [2000]	2.0 (35%)	1.7 (30%)	1.5 (26%)	0.5 (9%)	5.7	1995	Country	Annual
Oki et al. [2001]	1.8 (32%)	1.5 (27%)	1.5 (27%)	0.8 (14%)	5.6	1995	Country	Annual
Alcamo et al. [2000]	-	-	-	2.1 (37%)	5.7	1995	Watershed	Annual
Revenga et al. [2000]	3.1 (54%)	-	0.7 (12%)	1.7 (30%)	5.7[d]	1995	Watershed	Annual
Oki et al. [2001]	1.2 (21%)	0.5 (9%)	1.2 (21%)	2.7 (48%)	5.6	1995	Watershed[e]	Annual
Arnell [2004]	-	-	0.8 (14%)	1.4 (25%)	5.7	1995	Watershed	Annual
Vörösmarty et al. [2000]	3.2 (55%)	0.4 (7%)	0.4 (7%)	1.8 (31%)	5.8	1995	0.5°	Annual
Oki et al. [2001]	2.8 (49%)	0.6 (11%)	0.6 (11%)	1.7 (30%)	5.7	1995	0.5°	Annual
Arnell [2004]	-	-	0.8 (14%)	2.6 (46%)	5.7	1995	0.5°	Annual
Islam et al. [2007]	3.8 (62%)	0.5 (8%)	0.6 (10%)	1.2 (20%)	6.1	2000	0.5°	Annual
Hanasaki et al. [2008b][f]	2.4 (46%)	-	0.9 (17%)	1.9 (37%)	5.2	1995	1°	Subannual
This study	3.8 (62%)	0.6 (10%)	0.6 (10%)	1.1 (18%)	6.1	2000	0.5°	Annual
This study	3.0 (49%)	0.6 (10%)	0.8 (13%)	1.7 (28%)	6.1	2000	0.5°	Subannual

[a]Per class, population is given in billions, and the corresponding fraction of the total population is in percent.
[b]Year indicates the year of the population figure used for the estimates.
[c]Temporal resolution refers to the aggregation level of demand and availability. In the case of *Hanasaki et al.* [2008b] the aggregation was on a daily value over the period 1986–1995; this study used monthly mean values over the period 1958–2001.
[d]Approximately 200 million people were unallocated on the global scale.
[e]Transport factor α was set to 0.0 in the watershed-based estimate so that no upstream water was available to downstream reach along the river networks.
[f]Assessed by means of the cumulative withdrawal to demand ratio (CWD), which assesses the fulfillment of the demand on a subannual basis, divided into equivalent categories of no stress, medium stress, and high stress on the basis of WSI < 0.2, WSI < 0.4, and WSI ≥ 0.4, respectively. Shown are the values including both the effects of environmental flow and the reservoir operation scheme that are the most compatible with this study.

over the period 1986–1995. Identical to the study by *Hanasaki et al.* [2008b], the following regions emerge as suffering from moderate to severe water stress (Figure 6c): central North America, eastern South America, the Mediterranean, the Ukraine, central Russia, the Sahel, central Africa, India and SE Asia, NE China, Indonesia, and parts of Australia. Figure 7 shows the seasonality of water stress, highlighting these problem regions with considerable water stress as temporal variability is a decisive factor for water stress assessment especially for the regions experiencing wet and dry seasons such as the (sub)tropics. However, compared to the study of *Hanasaki et al.* [2008b] the inclusion of particular water resources in this study remediates water stress in areas where desalination and (nonrenewable) groundwater abstraction are important, e.g., the Arabian Peninsula for desalinated water use and NW India, NE Pakistan, NE China, central and western United States, Iran, and Saudi Arabia for nonrenewable groundwater abstraction. Thus, although the number of persons suffering from moderate water stress is roughly equal in both studies, our estimate of people suffering from severe water stress is lower (Table 3).

3.3. Comparison of Static Water Stress With Country Records

[30] The assessment on the basis of the monthly totals allows for a comparison of the dynamics of water stress against long-term observations. To obtain the historical trend of the WSI on a national scale, the monthly WSI was averaged over all pertinent cells. As a consequence, the country-averaged WSI is not capable of capturing water shortage that occurs in a particular part of a country (see section 3.3.2). Moreover, WSI levels associated with water scarcity may differ from those identified in section 2.1 This does not invalidate the comparison as indicators of water scarcity at the national level may differ from the general levels delineated by *Falkenmark et al.* [2007]. The water stress over the past 44 years was then compared with observed water shortage (i.e., drought) in the countries which are located in temperate, (sub)tropical and (semi)arid climates. We selected the following countries where people suffer periodic water shortage and past observed drought events were sufficiently recorded in the literature: the Netherlands, Japan, the Philippines, Afghanistan, Pakistan, Malaysia, Zimbabwe, and the state of Virginia. Figure 8 shows the simulated WSI of this study on both a monthly and an annual temporal scale for those countries over 1958–2001. The comparison shows that the simulated monthly WSI captures observed extreme or major drought events reasonably well in most of these countries (see sections 3.3.1 to 3.3.8 for detailed descriptions) while the simulated annual WSI is often too coarse in its temporal resolution to capture high intensities of WSI caused by seasonal drought events throughout the simulated period.

3.3.1. The Netherlands

[31] According to the Netherlands Drought Study (http://www.droogtestudie.nl/), the Netherlands experienced a very dry year (i.e., once every 50 years) in 1959 and an extremely dry year (i.e., once every 200 years) in 1976 [*Institute for Inland Water Management and Waste Water Treatment*, 2003]. The droughts of 1959 and 1976 were more intense than any other years because of a pronounced rainfall deficit, the latter year also being associated with extreme low flows of the River Rhine (recurrence period of 19 years for 2003 compared to 67 and 178 years for 1959 and 1976, respectively [*Beersma et al.*, 2004; *Beersma and Buishand*, 2004]). Other peaks are observed for the years 1974, 1981–1983, 1991 and 1995–1996 (Figure 8a) characterized by rainfall deficits and low flows for the Rhine. Large rainfall deficits caused the second driest summer on record for the

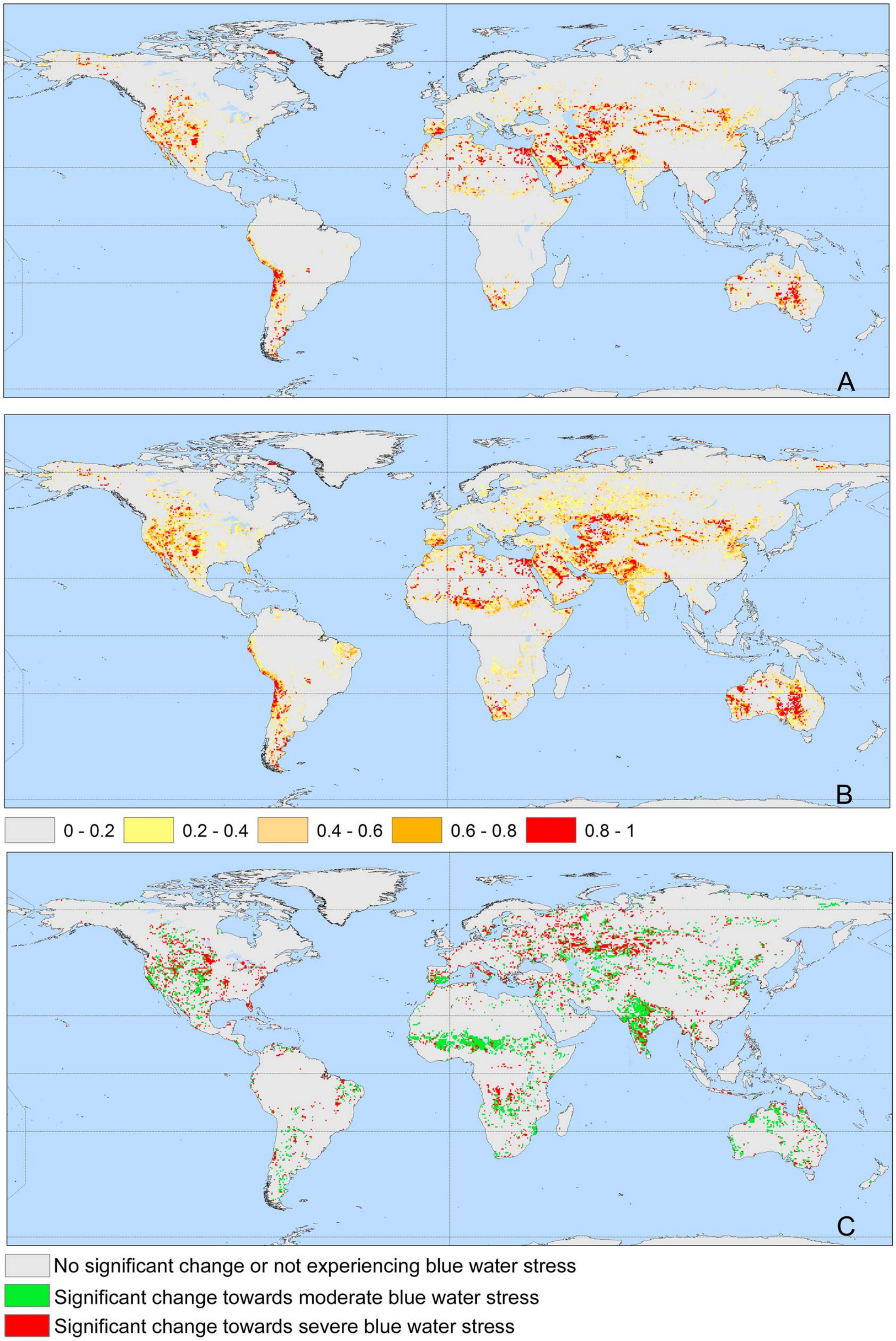

Figure 6. Mean water scarcity index based on (a) annual and (b) monthly totals of water availability and demand and (c) significant increase in water scarcity when increasing the temporal resolution from yearly to monthly (two-tailed t test with $\alpha = 0.05$).

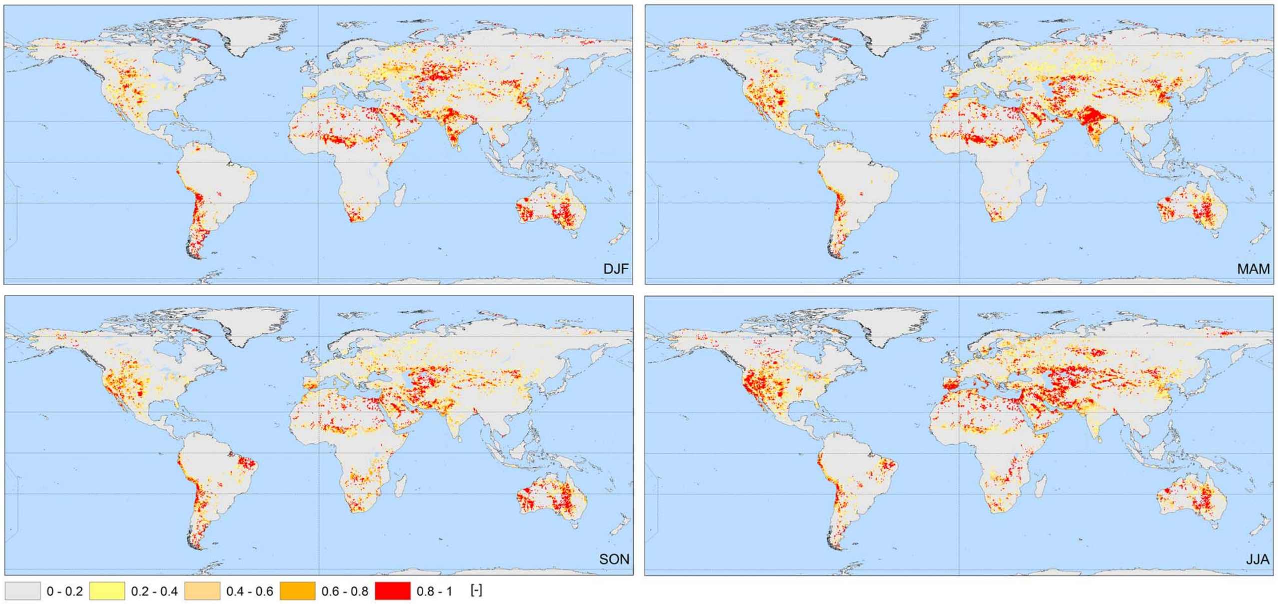

Figure 7. Mean seasonal water scarcity index over the period 1958–2001 (clockwise from top left).

Figure 8. Comparison of simulated, country-averaged monthly (red) and annual (black) water scarcity index (WSI; left axis) over 1958–2001 for (a) the Netherlands, (b) Japan, (c) the Philippines, (d) Afghanistan, (e) Pakistan, (f) Malaysia, (g) Zimbabwe, and (h) Virginia. Labels indicate years with severe water scarcity; symbols represent drought events expressed as days of drought for Japan (Figure 8b) and persons affected by drought events in million for the Philippines (Figure 8c).

year 1983 and caused the longest drought on record for the years 1995–1996. The simulated monthly WSI captures these drought events well. However, the simulated annual WSI is not capable of reproducing the high intensity of each major drought event (see Figure 8a).

3.3.2. Japan

[32] Figure 8b shows the estimated water stress and drought events for Japan. Drought events are represented by the number of days of drought, i.e., the total number of days on which the water supply was suspended for the three sectors (i.e., agriculture, industry and households and municipalities) per region (about 150 regions in Japan; in this case, state/province > region > city/town), by *MLIT* [2007]. Japan experienced intense water stress in the years 1973, 1978 and 1994. Water stress was particularly intense in the years 1978 and 1994 when for several weeks the water supply was suspended in the city of Fukuoka and Matsuyama for nearly 20 h a day [*Japanese Meteorological Agency* (*JMA*), 2002]. Overall, the severity of droughts is well approximated by the simulated monthly WSI with a notable exception for 1967. According to the *JMA* [2002], severe water shortage occurred particularly in southern Japan (i.e., Kyushu) in the year 1967, which is not captured by the country-averaged WSI. The simulated annual WSI significantly underestimates the intensity of water shortage throughout the simulation periods.

3.3.3. The Philippines

[33] Drought recurrently occurs in the Philippines associated with an effect of El Niño-Southern Oscillation (ENSO) [*Wilhite*, 1992]. Figure 8c shows the simulated WSI and the number of persons affected by drought events in the Philippines by the *National Disaster Coordinating Council* (*NDCC*) [1999]. The severe drought hit the Bicol region in the years 1968–1969 and the Central Luzon in the years 1972–1973 and affected nearly one million hectares of agricultural land in Central Luzon in the years 1982–1983 [*NDCC*, 1999; *Bankoff*, 2002]. Large rainfall deficits caused a severe drought in the years 1987–1988 resulting 46 of the 78 provinces being declared calamity compared with only 16 and 6 in the droughts of the years 1990 and 1991, respectively [*Wilhite*, 1992]. Drought in the years 1992–1993 affected around half a million hectares of agricultural land [*NDCC*, 1999]. In the years 1997–1998, 50% deficit of the average rainfall between October and March over 90% of the country [*Higashiura and Rees-Gildea*, 1998] caused reduced water supply throughout the country where 10% of water supply and 4 h of daily water service were reduced in Manila and irrigation water supply for 27,000 ha was cut off [*Jegillos*, 2007]. Overall, the observed major drought events are relatively well approximated by the simulated monthly WSI with exceptions of 1992–1993 and 1995 when drought events mainly affected agricultural lands and particular regions, respectively.

3.3.4. Afghanistan

[34] Afghanistan, characterized by (semi)arid climate, suffers from periodic droughts [*Qureshi*, 2002]. Two intense droughts hit Afghanistan in the years 1970–1971 and 2000–2001, which were more severe than any other years [*Alim and Shobair*, 2002]. Precipitation was only around 60% of the average in 1970–1971 [*Alim and Shobair*, 2002]. All ephemeral rivers dried out in early spring and perennial rivers (e.g., Helmand, Farah Rud, and Murghab) dried out in early to mid summer in 2000–2001. Two intense droughts in 1970–1971 and 2000–2001 agree well with the simulated monthly WSI (see Figure 8d). The simulated annual WSI also captures these droughts although it largely underestimates the intensity of each event.

3.3.5. Pakistan

[35] Pakistan being mostly (semi)arid is prone to frequent droughts mainly caused by rainfall deficits during the monsoon season. After the mid-1950s, the most intense drought occurred in the year 1999 and continued up to the year 2002 [*Ahmad et al.*, 2004]. This intense drought aggravated the water supply of the country's already high water-stressed situation [*Asian Development Bank*, 2005] resulting in a water shortage of up to 51% of normal supply as the total flow in major rivers declined more than 30% [*Ahmad et al.*, 2004]. The simulated monthly WSI captured the worst drought event of 1999–2001 (see Figure 8e). However, the simulated monthly WSI also shows two other similar peaks during the mid-1960s and the year 1974 even though droughts in these periods were not as intense as the worst drought of 1999–2001. As this study used the year 2000 as benchmark, past water demand is overestimated. This is likely a main cause of the too high peaks of 1960s and 1974. The simulated annual WSI also shows the similar trend of water stress with the monthly WSI and captures the worst drought event of 1999–2001. In Pakistan, water stress or water shortage, is persistent or relatively nonseasonal over the years, which enables the annual totals of water availability and water demand to reflect the intensities of water stress close to that of the monthly WSI.

3.3.6. Malaysia

[36] Two severe droughts hit Malaysia in its recent history. One occurred in the year 1983 and continued 6 months [*Daily Express*: *Independent National Newspaper of East Malaysia*, 2008] and the other occurred in the year 1998 associated with the ENSO [*Shaaban and Sing*, 2003]. The drought of 1998 particularly affected 1.8 million residents in South Kuala Lumpur City and disrupted domestic water supply for a certain period from April to September [*Shaaban and Sing*, 2003]. Most parts of Sabah received less than 25% of the average rainfall from January to April in 1998 [*Shaaban and Sing*, 2003]. The recurrence interval of 1998 drought was estimated to be more than 40 years in some parts of Malaysia [*Shaaban and Sing*, 2003]. The simulated monthly WSI of this study agrees well with the two worst drought events of 1983 and 1998 (Figure 8f) while the simulated annual WSI is not capable of reproducing the drought events which are characterized by the high peaks because of their large seasonality.

3.3.7. Zimbabwe

[37] The years 1980–1981 showed very wet conditions reminiscent of the mid-1970s and annual rainfall was over 150% of the average in some areas [*Bratton*, 1988]. However, Zimbabwe experienced the worst drought in the following years of 1982–1984 [*Bratton*, 1988; *Wilhite*, 1992; *Maphosa*, 1994]. The drought of 1982–1984 was the most intense on record because of the rainfall deficits in three consecutive years [*Wilhite*, 1992]. This drought caused depletion of water reservoirs and water shortage was prevalent throughout the country while domestic water supply was rationed in urban areas [*Bratton*, 1988; *Wilhite*, 1992; *Maphosa*, 1994]. Other major droughts hit Zimbabwe in the years 1986–1987, 1991–1992 and 1994–1995 which particularly affected agricultural production [*Kinsey et al.*,

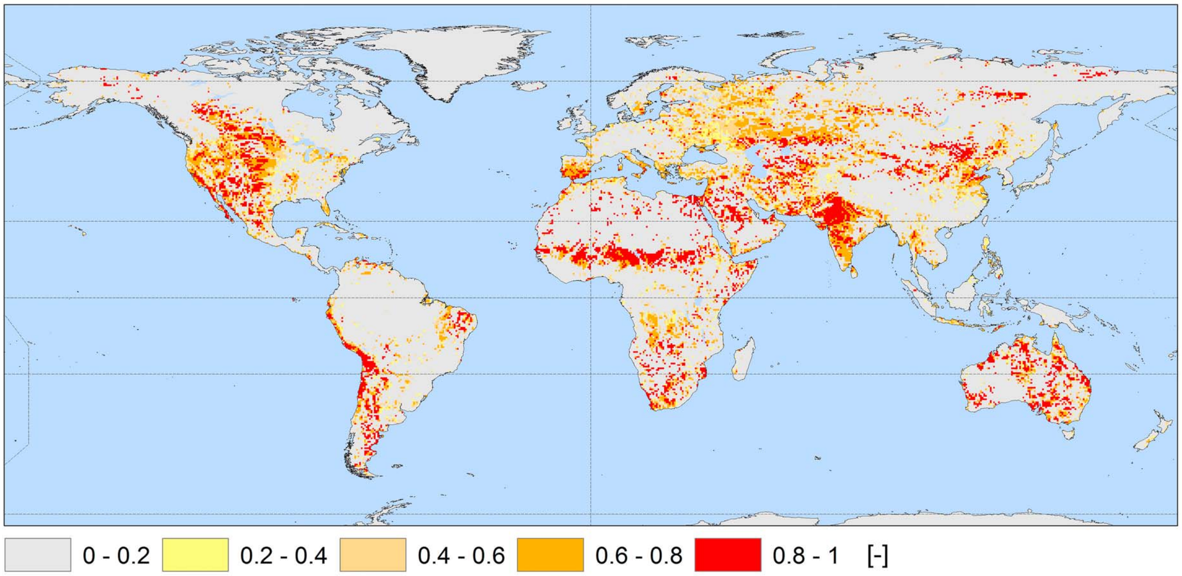

Figure 9. Dynamic water stress index (DWSI) based on monthly WSI ≥ 0.4 over the period 1958–2001.

1998]. The severity of the droughts are overall well approximated by the simulated monthly WSI and the periods of wet years by low WSI during the mid-1970s and 1980–1981 are captured as well (Figure 8g). The simulated annual WSI, on the other hand, shows the similar trend of WSI with the monthly WSI but it underestimates the intensity of each drought event.

3.3.8. Virginia

[38] Virginia, located halfway the eastern coast of the United States, is classified as a humid subtropical climate. Since the mid-1900s, Virginia has experienced several major or statewide droughts (USGS, http://va.water.usgs.gov/drought/histcond.htm). The statewide drought of 1962–1971 was the most intense in its duration because of extensive low-flow conditions over several years and the recurrence interval of the drought was estimated as 50 to 80 years [*Nuckels et al.*, 1990]. The prolonged drought of 1962–1971 with its severity was well reproduced by the simulated monthly WSI as shown in Figure 8h. The drought of 1988, being not only statewide but also nationwide, was the most severe in its intensity because of large rainfall deficit. Another major drought hit Virginia from 1998 to 2002 following the record wet months in which Virginia received well above-average rainfall [*Drought Monitoring Task Force*, 2002]. The drought of 1998–2002 was less prolonged but as severe as in its intensity compared to that of 1962–1971. While the droughts of 1962–1971, 1988 and 1998–2002 are well reproduced by the simulated monthly WSI (Figure 8h), the drought of 1980–1982, being less intense compared to other droughts, is less well approximated as it mainly affected the James River Basin (recurrence interval of 80 years compared to 15 years for the other regions of Virginia). Similar to the monthly WSI, the annual WSI captures the drought events reasonably well as drought events are fairly persistent in Virginia.

3.4. Seasonality, Severity, and Dynamic Water Stress

[39] Figure 9 shows the dynamic water stress (equation (4)) calculated over the 44 year period 1958–2001. By definition, it identifies all areas subject to actual water scarcity (WSI ≥ 0.4) and the potential damage given the persistence and recurrence of water scarcity. Highlighted are those areas experiencing frequent and persistent water scarcity (DWSI ≥ 0.6), such as India, central North America, Sahel, parts of the Pacific coast of South America and NE China, mostly associated with a irrigation water demand. On the other hand, in SE United Kingdom, Russia and part of Brazil, DWSI is lower, indicating the existence of infrequent or intermittent periods of actual water scarcity. The DWSI equally identifies the Philippines, Pakistan, Afghanistan and Virginia as regions experiencing frequent periods of actual water stress and the Netherlands, Japan, Malaysia and Zimbabwe as regions experiencing infrequent water stress as shown in Figure 8.

4. Discussion and Conclusions

[40] With the study of *Hanasaki et al.* [2008a, 2008b], this study assessed global blue water stress with a finer temporal resolution than annual totals. Net blue water demand was estimated for 2000 as benchmark year following the methods used in previous studies [*Vörösmarty et al.*, 2000; *Oki et al.*, 2001; *Alcamo et al.*, 2003a; *Flörke and Alcamo*, 2004; *Siebert and Döll*, 2008] but with the latest available data sets, with the additional inclusion of seasonal variations in the domestic water demand, accounting for desalinated water use and the nonrenewable groundwater abstraction and with consideration of the spatially variable recycling ratios for the industrial and the domestic sector, and green water availability for the irrigated areas, thus assessing water scarcity in terms of net rather than gross blue water demand. Blue water availability was computed by means of the macroscale hydrological model PCR-GLOBWB over the period 1958–2001 with inclusion of the prognostic reservoir operation scheme similar to *Haddeland et al.* [2006].

[41] Using the annual totals of water demand, the estimated number of persons suffering from moderate to severe water stress in the year 2000 is 1.7 billion and is lower than that of previous studies (Table 3). This number increases more than

40% to 2.5 billion when the monthly temporal variability over this period is considered. This increase is largely attributable to the inclusion of climate variability although seasonal variation in demand also plays a role, particularly where blue water availability is large but seasonal as is the case for the Asian monsoon belt.

[42] *Meigh et al.* [1999] pointed out that water shortages often become apparent only as occasional deficits at certain times of the year. Both the comparison of the assessments at the annual and the monthly scale (Figure 6) and the DWSI (Figure 9) identify many regions where the annual resolution is too coarse to identify the occurrence of water stress. Moreover, the long-term assessment of water stress compared with the country-based drought events reveals that the annual resolution significantly underestimates the intensity of water stress in countries where drought events are seasonal (Figure 8). Our long-term assessment of monthly water stress and the DWSI illustrate *Meigh et al.*'s [1999] argument for the first time on a global scale. The study also identified regions where actual water scarcity is a frequent and prolonged issue such as India, central North America, Spain, and NE China, next to those where actual water scarcity is infrequent and intermittent such as SE United Kingdom, Brazil, and Russia.

[43] Various sources of uncertainty are associated with the estimates of water demand and water availability used in this study. Data availability and consistency are major constraints to the definition of water demand at the scale of an individual year, in this case 2000, let alone a substantial period, for example the years 1958–2001. This explains the choice for a single benchmark year. The comparisons with actual water scarcity for seven countries and one state indicate (Figure 8) that the results are relatively insensitive to this choice, with past events being successfully identified regardless of the demand estimated only for the year 2000. It thus appears that climatic variability, reflected in local rainfall deficits and regional low-flow conditions, is often the main determinant of water stress in developed countries. Figure 8 also shows that water demand likely plays a significant role in emerging countries such as Pakistan when including the effects of an increasing population and heightened water demand. Therefore, reliable estimates of water demand are indispensable to improve the assessment of water stress especially when considering the increased standard of living in populous emerging and developing countries (e.g., China, India, and Pakistan) [*Meinzen-Dick and Rosegrant*, 2001]. Notwithstanding the scarcity of data, substantial improvements have been obtained in the assessment of the irrigation water demand which is the largest amount among all the sectors, comprising 70% of the total water withdrawal (Table 2). Estimates of the irrigation water demand are robust and compare well with the reported values of the AQUASTAT database (Figure 2). Important sources of uncertainty for irrigation water demand are biases in climatic forcing, discrepancies in irrigated area, poor estimates of the irrigation efficiency and imprecise and prescribed calendars of multiple cropping systems.

[44] Although this study allows for the assessment of the vulnerability of the present-day population to water stress, the assessment of future water including the effect of climate change and socioeconomic developments (e.g., IPCC scenarios) is of greater scientific and societal importance. As this study confirms and identifies areas that are liable to water scarcity by increasing the temporal resolution, as it explores new data resources and approaches to assess water scarcity and as it highlights sources of uncertainty, it may help to increase the reliability of coming assessments of future water scarcity.

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